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THIRD QUARTERLY PROGRESS
REPORT FOR PERIOD ENDING
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RESEARCH & DEVELOPMENT OF OPEN CYCLE FUEL CELLS

Contract No. NAS 8-5392

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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RESEARCH AND DEVELOPMENT OF OPEN-CYCLE FUEL CELLS

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PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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INTRODUCTION

This report is the Third Quarterly Progress Report issued under Modification Number 4 to Contract NAS 8-5392. Progress during the period of February 16, 1965 through May 15, 1965 is covered herein.

ABSTRACT

The computer program to optimize space radiators with respect to weight has been completed and design charts presented. The study of fuel cell startup techniques has been initiated and the effect of temperature gradient on electrolyte concentration gradient determined. The revision and improvement in the computer program for the mathematical representation of the static vapor pressure method of water removal are described. The approaches to develop a mathematical model for cell degradation and to expand the reliability study of fuel cells are presented.

SUMMARY

An analysis was performed and programmed for solution by a digital computer to optimize space radiators with respect to weight. A mathematical equation and several design charts are presented which show the effect of various input conditions on the optimum weight of the radiator.

The results of a study on fuel cell startup techniques are reported. An analysis is presented for determining the effect of temperature gradient on the concentration gradient in the electrolyte. In general, for a properly filled fuel cell stack there should be no flooding problems for a large temperature gradient.

The revisions and improvement in the computer program for the mathematical model of static moisture removal process are described.

The approach to develop a mathematical model of cell degradation is presented. Additional work is needed to arrive at a meaningful model.

A reliability study is initiated to compare the reliability of various series-parallel fuel cell configurations.

1.0 COMPUTER PROGRAM FOR FUEL CELL PARAMETER OPTIMIZATION

The existing computer program (IBM 704) for fuel cell system parameter optimization is being modified and extended to include the use of secondary batteries for power peaking on irregular load profile missions. Subroutines are being added which compute the properties of reactant storage vessels and radiators as functions of the system operating parameters so that they can influence the optimization of the overall system. The effects of adding a water recovery subsystem will also be considered by the expanded program.

1.1 Fuel Cell-Rechargeable Battery Combination

A digital computer program to size a battery-fuel cell combination for minimum total weight has been written. This program was refined to accomodate certain minor changes. The method of modifying the power profile to account for the power required for recharging the batteries was changed from a power addition to a current addition technique. A more accurate approximation of cell area was incorporated. The portions of the program affected by the changes are being de-bugged. During the next reporting period, a large number of problems covering a broad range of conditions will be solved and used to obtain design curves.

1.2 Space Radiators

A brief summary of the analysis to optimize space radiators is given below. This analysis was programmed for solution by a digital computer. Several problems were solved with the program to obtain the attached design curves and to develop a mathematical equation for determining minimum radiator weight.

1.2.1 A Brief Summary of the Analysis

Radiator designs are computed for arbitrarily selected pairs of values of inside dimension of fluid duct, Di, and number of parallel ducts, N . The optimum design is selected on the basis of minimum weight.

$$W_{rad} = W_{fin} + W_{duct} + W_{liquid} + W_{bumper}$$

$$W_{rad} = L_h (1 + f) L_w d_h N p_f + \frac{P (D_o^2 - D_i^2) L_w N p_d}{4 \; D_i}$$

$$+ \frac{D_i^2 \; L_w \; p_l \; N}{E_a} \quad + \frac{P_b (D_{ob}^2 - D_{ib}^2) \; L_w \; N \; p_b}{4 \; D_{ib}}$$

If the ducts were to be circular,

$$W_{rad} = L_h \; (1 + f) \; L_w \; d_h \; N \; p_f \quad + \frac{\pi \; (D_o^2 - D_i^2) \; L_w \; N \; p_d}{4}$$

$$+ \frac{\pi \; D_i^2 \; L_w \; p_l \; N}{4} \quad + \frac{\pi \; D_{ob}^2 - D_{ib}^2) \; L_w \; N \; p_b}{4}$$

L_w, D_o, D_{ib}, D_{ob}, L_h, and d_h can be expressed in terms of the initially selected values of D_i and N by using the following methods.

The tube length, L_w , is based on the allowable pressure drop through the system

$$L_w = \frac{D_i \;\; P}{2 \; f_f \; p_l \; v^2}$$

where f_f is the Fanning friction factor and the fluid velocity, v, is:

$$v = \frac{4 \quad w}{N \, p_1 \, \pi \, D_i^2} \qquad\qquad w = \frac{Q}{C_p \, \Delta \, T_1}$$

The outside diameter of the tubes, D_o, based on the desired probability of meteroid puncture which is in turn derived from the probability of success of the radiator, R_p

$$D_o = D_i + 2 \, d_o$$

and

$$R = \frac{100 \, (1 - R_p^{1/n}) \, A_e}{C' \, N \, L_w \, (D_i + 2 \, d_o)}$$

where n is the mission time in days, and C' is an orientation factor (1.0 in deep space, 0.5 in earth orbit). Reference (1) provides a tabular relationship between R and d_o which is used with the above equation to fix d_o and thus D_o.

The inside and the outside diameter of the bumper, used to increase the radiator probability of success by shielding it from micrometeroids, D_{ib} and D_{ob} respectively, are determined on the basis of a theory presented by F. L. Whipple.[1]

$$D_{ib} = D_o + 4 \, d_o$$

$$D_{ob} = D_o + 4.2 \, d_o$$

The fin width, L_h, is computed by the following procedure:

Step 1 - Determine the optimum fin effectiveness[2], Z. Obtain z by solving,

$$13A_o z^4 + 10A_1 z^3 + 7A_2 z^2 + 4A_3 z + A_4 = 0$$

Then, $Z = A_4 + A_3 z + A_2 z^2 + A_1 z^3 + A_o z^4$

Where A_o, A_1, A_2, A_3 and A_4 are constants and can be obtained from reference 2.

Step 2 - Determine the coolant outlet temperature, T_{12},

$$T_{12} = T_{11} - \Delta T_1$$

Step 3 - Determine the radiator constant C_1

$$C_1 = s\,(e_a + e_b)$$

Step 4 - Determine the heat received from environment by both surfaces of a unit of fin area.

(see next page)

$$C_2 = S\,(a_a \cos i + F_a\, a_a\, b_m \cos j + F_{ax}\, a_a\, b_x \cos m$$

$$+ F_b\, a_b\, b_m \cos j + F_{bx}\, a_b\, b_x \cos m) + s\,(F_a e_a + F_b e_b)\, T_m^4$$

$$+ s\,(F_{ax} e_a + F_{bx} e_b)\, T_x^4$$

<u>Step 5</u> - Determine the fin width, L_h

$$L_h^o = \frac{1}{2\ Z} \left[\frac{2Q + 2C_2 L_w\ ND_o}{C_1\ L_w\ N\,(T_{11}^4 \quad T_{12}^4)} - D_o \right]$$

L_h^o is the initial value of L_h. It is modified according to

$L_h = L_h^o\ (L_{w_2} / L_w)$ until the tube length, L_w, becomes equal to the theoretical length L_{w_2}. The value of L_{w_2} can be determined by the method given in reference 2. By using this procedure, the value of inlet wall temperature T_{w_1}, is also calculated.

The fin thickness, d_h, is given by,

$$d_h = \frac{C_1\, T_{w_1}^3\, L_h^2}{K\ z}$$

1.2.2 Discussion

Several computer runs were made with the program to determine optimum radiator weight for various heat loads and subjected to various input conditions. It was assumed that the radiator is made of aluminum and that 62.5% ethylene glycol by weight is used as the coolant. The temperature and pressure drops in the coolant were assumed to be 22° K and 1390 Kg/sq. meters respectively.

Figures 1, 2, 3, and 4 give the optimum radiator weight for various mission durations when the radiator probability of success was 0.999 and when the inlet coolant temperature varied between 311° K and 355° K. Figure 5 presents the effect of the desired probability of success of the radiator on the optimum weight. In order to make this figure more useful, the mission duration was selected to be 14 days, which is typical for lunar missions. Figure 6 shows the effect of the heat input from environment on the optimum weight.

1.2.3 A Mathematical Equation to Determine the Optimum Radiator Weight for Various Conditions

The results from the computer runs were used to develop the following equation for optimum weight, W.

$$W = C_1 \left(\frac{Q}{200}\right)^{C_2} n^{C_3} \left(\frac{0.01}{1 - RPS}\right)^{C_4} \left(\frac{311}{T_{11}}\right)^{C_5}$$

where:

$$C_1 = 0.3217$$

$$C_2 = 1.56 + 0.0005 \left(\frac{Q}{200}\right) + \frac{2 \times 10^{-6}}{1 - RPS} + 0.0004\, n$$

$$C_3 = 0.208\left(\frac{0.01}{1 - RPS}\right)^{0.20808 - 0.000408 \frac{0.01}{1 - RPS}} + 0.0005\,n$$

$$C_4 = 0.2088 + 0.000521\left(\frac{0.01}{1 - RPS}\right)^{1.04}$$

$$C_5 = -31.6 + 0.0086\left(\frac{0.01}{1\text{-}RPS}\right) + 0.0007\,n + 52.5\left(\frac{311}{TI_1}\right)$$

$$+ \frac{Q}{200}\ (0.030)$$

It should be noted that the above formula gives weights within $\pm 5\%$ and is valid only for the conditions given below:

(a) Radiator material - aluminum

(b) Type of coolant - 62.5% Ethylene glycol (by weight)

(c) Coolant pressure drop - 1390 Kg/Sq. meters

(d) Coolant temperature drop - 22° K

(e) Heat input from the environment - 240 kcal/hour sq. meters

(f) A bumper type of shielding is used to protect the radiator tubes from meteroids. F. L. Whipple's theory is used for calculation purposes.

(g) 311° K $\leq$ inlet coolant temperature $\leq$ 355° K

(h) 0.99 $\leq$ radiator probability of success $\leq$ 0.9999

(i) 200 kcal/hour $\leq$ heat load $\leq$ 10,000 kcal/hour

(j) 0.5 days $\leq$ mission duration $\leq$ 100 days

NOMENCLATURE

D_i	=	inside tube diameter, m
D_o	=	outside tube diameter, m
F_a	=	view factor, sunny side of radiator to first environmental surface
F_{ax}	=	similar to F_a, but to second environmental surface
F_b	=	similar to F_a, but from dark side
F_{bx}	=	similar to F_b, but to second environmental surface
f	=	ratio of narrow fin width to wide fin width
f_f	=	fanning friction factor
h	=	heat transfer coefficient, kcal/m^2 hour ° K
k	=	thermal conductivity of fin, kcal/m^2 hour ° K
L_h	=	fin width, m
L_w	=	tube length, m
N	=	number of tubes
ΔP	=	pressure drop through radiator, kg/m^2
Q	=	rejection heat load, kcal/hour
S	=	solar constant, kcal/m^2 hour
T_{11}	=	inlet coolant temperature, ° K
T_{12}	=	fin temperature at inlet side, ° K
T_{w_2}	=	fin temperature at outlet side, ° K
v	=	coolant velocity, m/hour
w	=	coolant flow rate, kg/hour

b_m = reflectivity of first environmental surface

b_x = reflectivity of second environmental surface

i = angle between radiator and sun

j = angle between radiator and first environmental surface

m = angle between radiator and second environmental surface

d_h = fin thickness, m

d_o = tube wall thickness, m

e_a = emissivity of sunny surface of radiator

e_b = emissivity of dark surface of radiator

a_a = absorbtivity of sunny surface of radiator

a_b = absorbtivity of dark surface of radiator

p_d = density of duct material, kg/m^3

p_f = density of fin material, kg/m^3

p_l = density of liquid, kg/m^3

s = Stephan-Boltzman constant, kcal/m^2 hour °K^4

D_{ib} = inside diameter of the bumper, m

D_{ob} = outside diameter of the bumper, m

P = wetted perimeter of the duct, m

P_b = inside perimeter of the bumper, m

E_a = a conversion number relating flow area, (4 for a circular tube)

b = density of bumper material, kg/m^3

T_1 = temperature drop in the coolant, °K

C_P = specific heat of the coolant kcal/Kg °K

A_e = projected area of the earth, m^2

n = mission time, days.

2.0 FUEL CELL STARTUP TECHNIQUES

A study of launch pad and remote startup was initiated. The problems associated with the present in-duct heater arrangement were considered in particular. This method has several advantages and disadvantages. Some of these are:

Advantages:

(a) The heat is released near the object which is to be heated.

(b) The heaters are easy to install and, once installed, they will be protected from handling damages.

(c) Electrical energy is readily available and easily controlled.

Disadvantages:

(a) Electrical leads must pierce the canister.

(b) A temperature gradient will be induced in the stack. The temperature gradient through the stack could cause a potassium hydroxide concentration gradient. If this concentration gradient is sufficient to flood the cell, the method of heat-up would be acceptable.

2.1 Analysis

An analysis was performed to determine the effect of temperature gradient on the concentration gradient. To simplify the analysis, the steps preceding the application of heat to the module were assumed to be:

(a) Hydrogen and oxygen introduced into the fuel cell system.

(b) The water cavity is evacuated to a pressure equal to that required to maintain 40% concentration at the present cell temperature.

(c) All gas systems are sealed (gas is vented, if necessary, to maintain the reactant system at a constant pressure).

When heat is applied to the system and a temperature gradient developed, there will be a redistribution of the water contained within the electrolyte. This analysis is valid if the time constant of the system is disregarded and if it is assumed that a concentration equilibrium has been established.

If there are no sources or sinks for the water or potassium hydroxide, then a simple relation exists for the conservation of mass within the stack.

W_{TOT} = total weight of electrolyte within the stack of N membranes.

If each membrane was filled with W_F of electrolyte at concentration K , then

$$W_{TOT} = NW_F \quad \text{at fill}$$

At any other time

$$NW_F = W_1 + W_2 + \ldots + W_N$$

but $$W_i = \frac{W_{KOH}}{K_i} \qquad i = 1, 2 \ldots N$$

The weight of potassium hydroxide (W_{KOH}) is the same in each membrane and must be constant with respect to time. It is given by KW_F . Thus,

$$NW_F = \sum_{i=1}^{N} W_i = \sum_{i=1}^{N} \frac{W_{KOH}}{K_i} = \sum_{i=1}^{N} \frac{KW_F}{K_i} = KW_F \sum_{i=1}^{N} \frac{1}{K_i}$$

or

$$\frac{N}{K} = \sum_{i=1}^{N} \frac{1}{K_i} \quad \text{at all times.}$$

The partial pressure P_i , concentration K_i , and temperature T_i of any membrane are related by

$$K_i = 48 - 1.75 \times 10^{-4} P_i^2 \; e^{-0.0448 (T_i - 195)}$$

at equilibrium. For any known temperature gradient, the concentration gradient can be found by iterating on $F = P_i$ (for all i) until the condition

$$\frac{N}{K} = \sum_{i=1}^{N} \frac{1}{K_i} \quad \text{is satisfied.}$$

2.2 Discussion

If the temperature gradient is linear, the problem is greatly simplified. N is set equal to 2 and the end point temperatures are used. This problem has been solved for various temperature gradients having end point temperatures T and 195° F ($T \lesssim 195$). The results are presented in Figure 7.

The conservation of the mass of potassium hydroxide in each membrane provides a convenient expression for the relative volume occupied by the electrolyte at any concentration.

$$W_{KOH} = pVK = \text{a constant.} \quad \text{Where } p \text{ is the specific gravity.}$$

Thus

$$\frac{V_2}{V_1} = \frac{p_1 K_1}{p_2 K_2}$$

Condition 1 is taken to be the fill condition, and was assumed to be 40 percent. Figure 8 shows the relative volume as a function of the concentration. Flooding will occur when the electrolyte has completely filled the electrodes or support plaques and a small amount of water is added. Approximate values for 0.02 inch and 0.03 inch asbestos membranes are

$$\frac{V_2}{V_1} = 1.939 \text{ and } 1.473 \text{, respectively.}$$

The concentrations for which these limiting values would be obtained are 25.5 % and 31.0 %. Figure 1 shows that these concentrations should not occur.

For cells which have been improperly filled during construction of the stack, there may be problems. For a cell whose support plaques are two-thirds full, flooding will occur when $\frac{V_2}{V_1}$ is equal to 1.27 for a 0.03 inch membrane.

Figure 9 presents equilibrium partial pressure of water vapor over KOH solution for a sealed system having no sources or sinks and a linear temperature gradient = 195 - T.

The results which have been presented indicate that for a properly filled stack there should be no flooding problems due to a large temperature gradient in the stack. A quick check of the potassium hydroxide phase diagram shows that there should be no drying out problems. It should also be noted that the case considered represents the extreme of conditions which could occur. A module heat-up is a transient condition and the equilibrium concentration gradient would not be expected to occur. Interactions which would tend to counteract the establishment of large concentration gradients are:

(a) Heat is required to evaporate the water from the electrolyte, and heat is released when water is absorbed by electrolyte.

(b) Introductions of an inert in the water cavity would increase the time for diffusion of water vapor from point to point within the system.

3.0 MATHEMATICAL MODEL OF STATIC MOISTURE REMOVAL PROCESS

A number of revisions were made in the mathematical model to speed up the computational algorithms and to more accurately represent the conditions prevailing in the electrolyte support membranes of the fuel cell under transient conditions.

3.1 Revisions in the Model

The most significant revision in the model was the addition of a bulk flow term to describe the transport of KOH solution from point to point within the fuel cell structure. The effect of this flow can be represented by the following equation.

$$N_A = X_A \, (N_A + N_B) + \frac{D}{dz} \, (\Delta C_A)$$

The vectors $X_A \, (N_A + N_B)$ and $\frac{D}{dz} \, (\Delta C_A)$ in the above equation are the molar flux of a fluid A resulting from the bulk motion of the fluid and diffusion respectively. Since the number of moles of KOH remain constant in an electrolyte membrane,

$$\frac{d}{dt} \left(\sum C_{Bi} V_i \right) = 0$$

The two equations can be simultaneously solved to obtain the molar flux of the fluids across the boundaries of each element of volume into which the membrane is subdivided.

It should be noted that this revision also accounts for the change in volume of the elements, in the electrolyte, that are adjacent to a gas-liquid interface. Water and/or KOH enter or leave elements by bulk flow, diffusion, chemical reaction, evaporation and/or condensation. If the amount of fluid entering is different from the amount leaving, the volume of the element changes. This change in volume is represented by a movement of the interfaces which corresponds to a wetting or drying of the cell.

The speed and the mathematical stability of the computer program for the model has been improved to a large extent by considering the gas cavities as being in concentration equilibrium with the adjacent liquid elements. This approach makes it possible to treat the system as if it were composed of liquid only which in turn makes it possible to use a longer time interval per iteration. Note that this approach does not destroy any of the characteristics of the model, such as the concentration gradient across the length of the cell, since the following equation for the rate of change of concentration is still satisfied.

$$\frac{dc}{dt} = \frac{I}{nF\ V_2} \quad \frac{(12 - I)\,(C_{in}\, R_o T)}{P - C_{in}\, R_o\ T} \quad - \frac{(11 - I)\,(C_{out}\ R_o\ T)}{P - C_{out}\ R_o\ T}$$

$$+ \frac{D}{dz_1} \quad \frac{(C_L - C_{interface})}{(1 - X_A)\ (W)} \quad - \frac{D}{dz_2} \quad \frac{(C_{interface} - C_U)}{(1 - X_A)\ (W)} = 0$$

A more complete relationship between gas concentration, temperature, and interface concentration has also been established. This relationship can be evaluated more rapidly by computer than the exponential fit relationship used previously.

3.2 Computer Program for the Model

The computer program for the model has been modified to include all of the above revisions. It is now being debugged.

3.3 Nomenclature

N_A = molar flux of water crossing a boundary, $moles/cm^2\ sec$

N_B = molar flux of KOH crossing a boundary, $moles/cm^2\ sec$

X_A = molar fraction water, nondimensional

D = diffusion coefficient of water in KOH solution, cm^2/sec

C_A = water concentration, moles/cc

dz = length of diffusion path, cm

C_B = KOH concentration, moles/cc

V_1 = liquid element volume, cm^3

V_2 = gas element volumes, cm^3

F = Faraday's constant, coulombs/gram equivalent

R_o = universal gas constant, dyne - cm/mole °K

T = temperature, °K

W = gas element width, cm

I = cell current, amps

T = time, seconds

C_L = concentration of liquid filled element adjacent to gas cavity, moles/cc

C_V = concentration in liquid filled element adjacent to gas filled element opposite C_L, moles/cc

4.0 MATHEMATICAL MODEL OF CELL DEGRADATION

An attempt to develop a mathematical model to explain the voltage degradation in a fuel cell has been started. From past experience, it appeared that the voltage degradation could be represented by the following relationship

$$\Delta V = K \phi J$$

Where ΔV is the measured voltage drop per cell from initial conditions, K is a constant to be determined, ϕ is the total elapsed ampere hours, and J is the operating current density.

4.1 Empirical Determination of K

The results from tests on A-C breadboards # 1, # 2 and a few single cells (constructed under another contract, NAS 8-2696) were analyzed in an attempt to determine K. In order to arrive at a more meaningful value of K, it was necessary to reduce the test data so as to obtain the cell performance at constant condition, i.e., for constant values of electrolyte concentration, pressure, and temperature. Unfortunately, the test results were not sufficiently accurate and hence, this approach had to be dropped. An alternate, but approximate, method was therefore used. In this method, the effect of KOH concentration, cell temperature, purge, rate, etc., were neglected. The value of K so determined varied widely over the obtained test data. Additional test data would be necessary to establish a statistical confidence interval for the value of K.

5.0 RELIABILITY STUDY

A reliability study to compare the reliabilities of various series-parallel fuel cell configurations has been started. The reliabilities are being compared for two different major cases.

(a) Various systems were designed to meet identical voltage-power requirements but use different number of cells.

(b) Various systems were designed for identical power requirements and use same number of cells. A voltage converter would have to be used in conjunction with these systems to meet the voltage requirements.

In order to obtain a value for the overall system reliability, it was necessary to know the module reliability, which can be determined accurately by experiments. For the sake of comparing various systems at various levels of failure, an assumed value of module reliability should be sufficient.

6.0 CONCLUSIONS

The computer program on space radiators has been completed and design charts presented. A mathematical equation was empirically developed to determine the minimum radiator weight for various input conditions.

The study on fuel cell starting techniques resulted in an analysis to determine the effect of temperature gradient on the concentration gradient in the electrolyte. For a properly filled fuel cell stack there should be no flooding problems due to a large temperature gradient.

The improvements in the computer program for the mathematical model of static moisture removal process has resulted in decreasing the computing time required.

7.0 FUTURE WORK

(1) Expansion of the computer program for fuel cell parameter optimization will be continued. The mathematical equation to obtain a minimum radiator weight will be added as a subroutine to the existing program. Refinements in the computer program for fuel cell-rechargeable battery combination will be completed.

(2) The study on fuel cell startup techniques should be completed.

(3) Work will be continued to complete the revisions in the mathematical model of the static moisture removal process.

(4) Effort will be expended in the area of fuel cell module reliability.

References

1. Investigation of a 3 KW Stirling Cycle Solar Power System, Volume VII WADD-TR-61-122, Flight Accessories Laboratory, Wright-Patterson Air Force Base, Ohio, March 1962.

2. Digital Programs for Establishing Steady-State Space Radiator Performance, ASD-TDR-63-222, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, October 1963.

LIST OF ILLUSTRATIONS

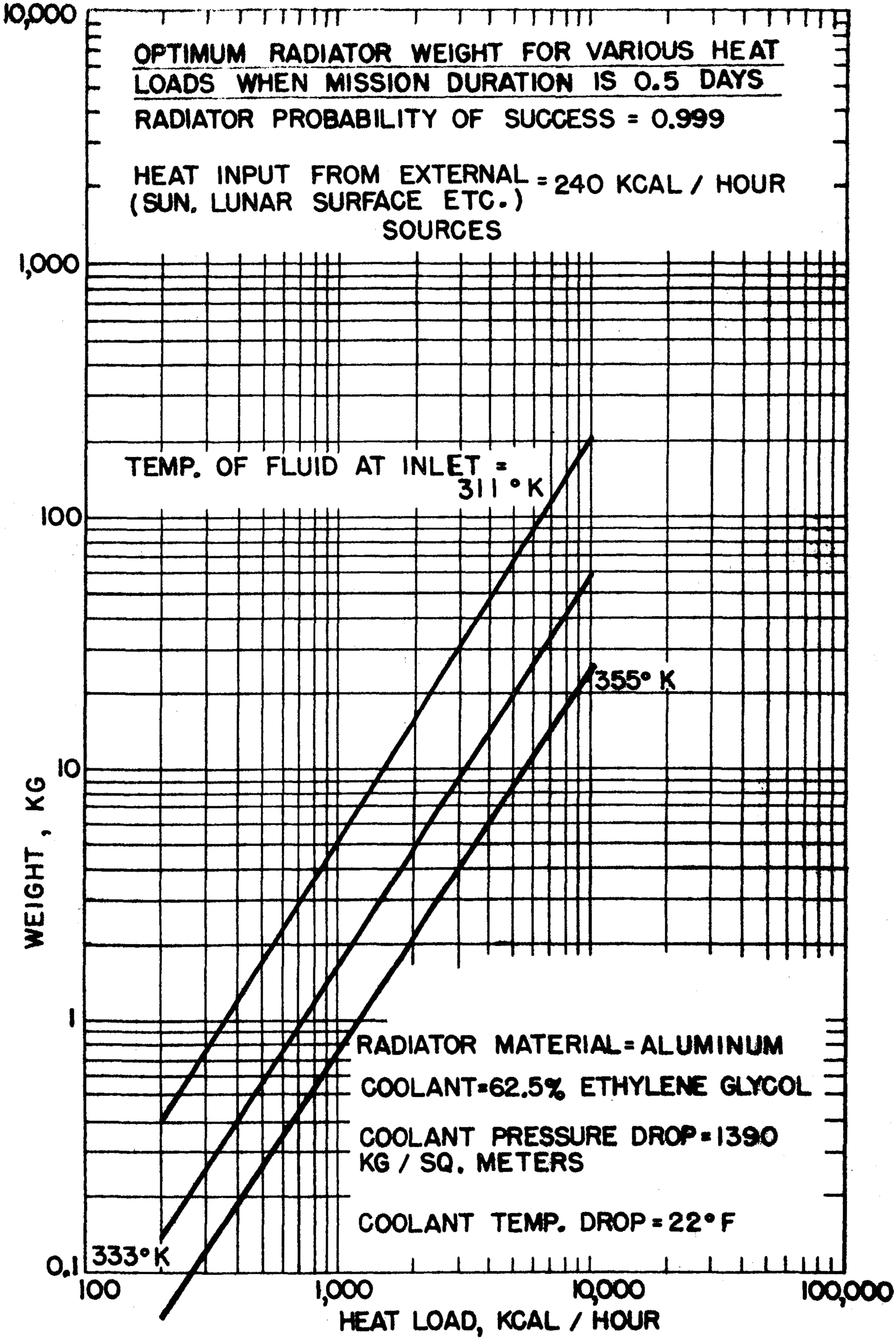
OPTIMUM RADIATOR WEIGHT FOR VARIOUS HEAT LOADS WHEN MISSION DURATION IS 0.5 DAYS
RADIATOR PROBABILITY OF SUCCESS = 0.999
HEAT INPUT FROM EXTERNAL (SUN, LUNAR SURFACE ETC.) SOURCES = 240 KCAL / HOUR
TEMP. OF FLUID AT INLET = 311 °K
355° K
333° K
RADIATOR MATERIAL = ALUMINUM
COOLANT = 62.5% ETHYLENE GLYCOL
COOLANT PRESSURE DROP = 1390 KG / SQ. METERS
COOLANT TEMP. DROP = 22° F
10,000
1,000
100
10
1
0.1
WEIGHT, KG
100
1,000
10,000
100,000
HEAT LOAD, KCAL / HOUR

FIGURE 1

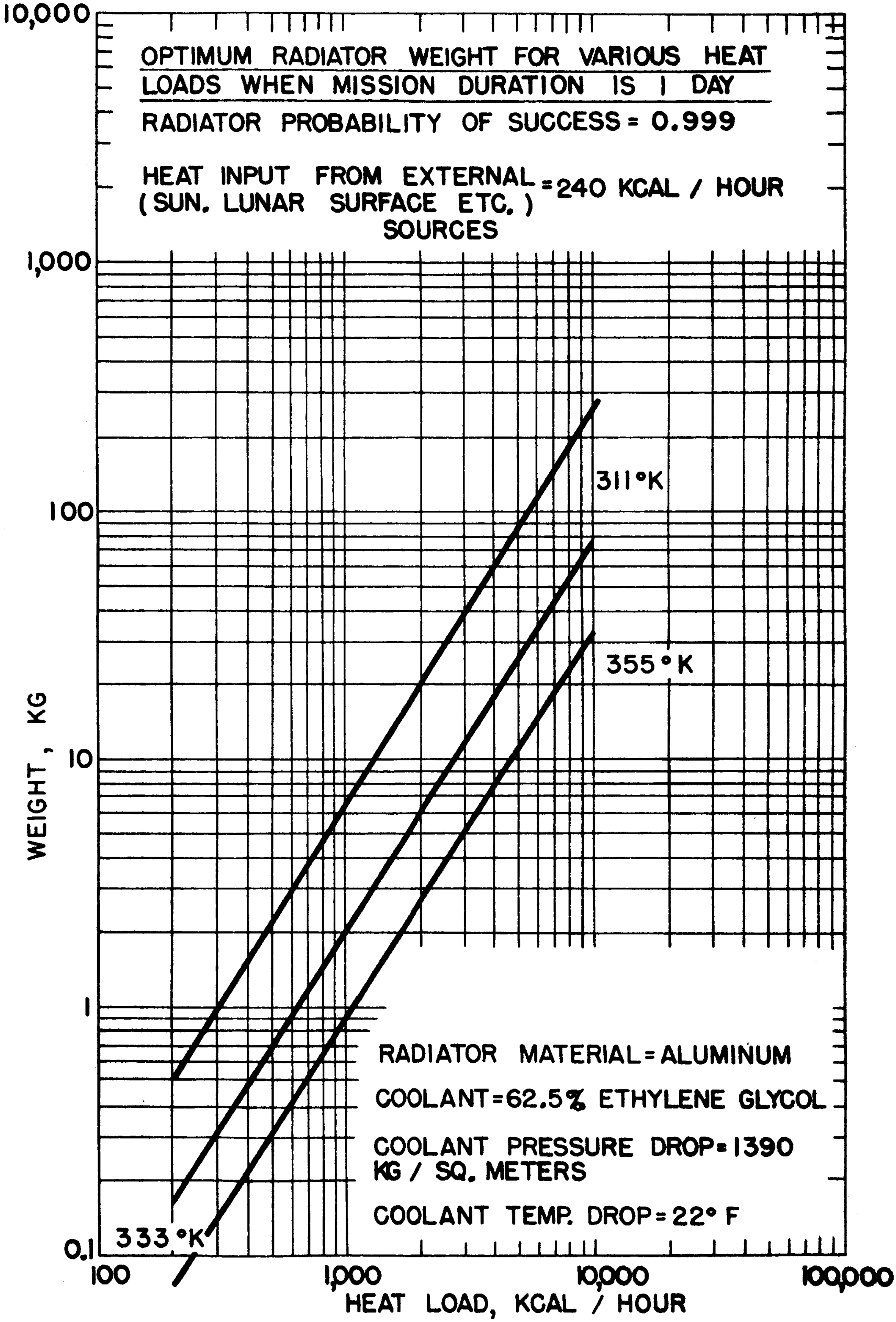
OPTIMUM RADIATOR WEIGHT FOR VARIOUS HEAT LOADS WHEN MISSION DURATION IS 1 DAY
RADIATOR PROBABILITY OF SUCCESS = 0.999
HEAT INPUT FROM EXTERNAL (SUN, LUNAR SURFACE ETC.) SOURCES = 240 KCAL / HOUR
311°K
355°K
333°K
RADIATOR MATERIAL = ALUMINUM
COOLANT = 62.5% ETHYLENE GLYCOL
COOLANT PRESSURE DROP = 1390 KG / SQ. METERS
COOLANT TEMP. DROP = 22° F
10,000
1,000
100
10
1
0.1
100
1,000
10,000
100,000
WEIGHT, KG
HEAT LOAD, KCAL / HOUR

FIGURE 2

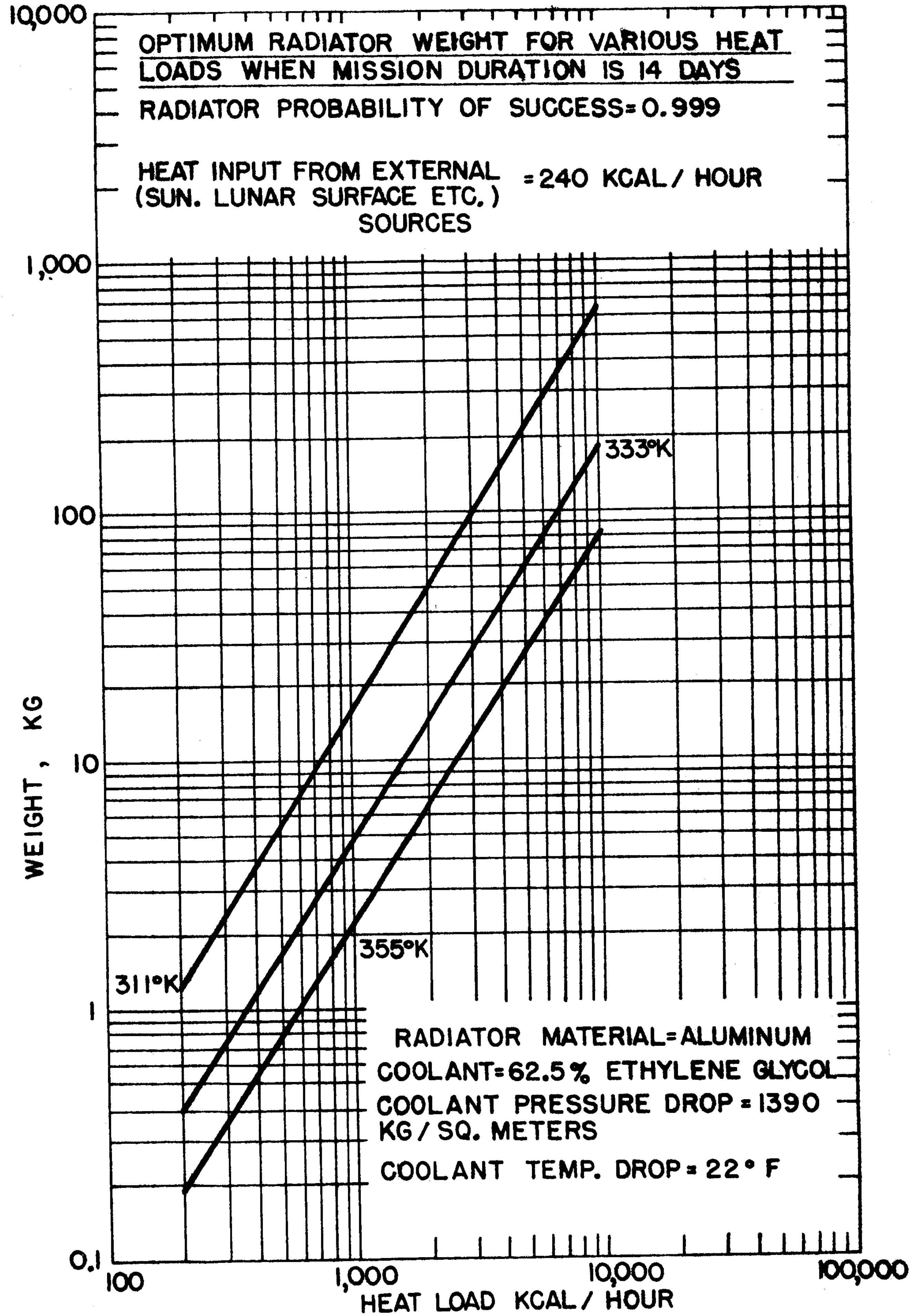
OPTIMUM RADIATOR WEIGHT FOR VARIOUS HEAT LOADS WHEN MISSION DURATION IS 14 DAYS
RADIATOR PROBABILITY OF SUCCESS = 0.999
HEAT INPUT FROM EXTERNAL (SUN. LUNAR SURFACE ETC.) SOURCES = 240 KCAL / HOUR
10,000
1,000
100
10
1
0.1
WEIGHT, KG
333°K
355°K
311°K
RADIATOR MATERIAL = ALUMINUM
COOLANT = 62.5 % ETHYLENE GLYCOL
COOLANT PRESSURE DROP = 1390 KG / SQ. METERS
COOLANT TEMP. DROP = 22° F
100
1,000
10,000
100,000
HEAT LOAD KCAL / HOUR

FIGURE 3

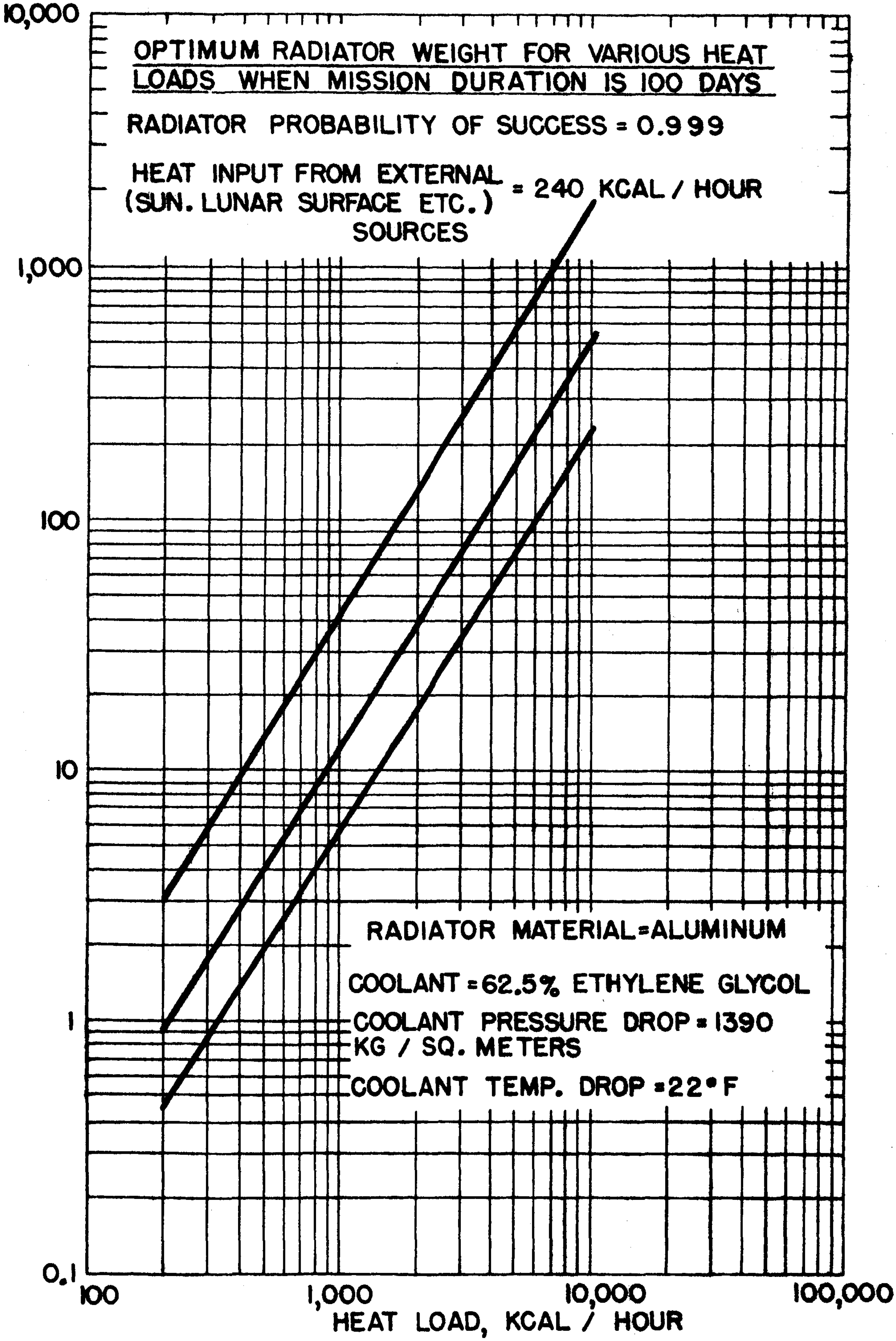
OPTIMUM RADIATOR WEIGHT FOR VARIOUS HEAT LOADS WHEN MISSION DURATION IS 100 DAYS
RADIATOR PROBABILITY OF SUCCESS = 0.999
HEAT INPUT FROM EXTERNAL (SUN. LUNAR SURFACE ETC.) SOURCES = 240 KCAL / HOUR
RADIATOR MATERIAL = ALUMINUM
COOLANT = 62.5% ETHYLENE GLYCOL
COOLANT PRESSURE DROP = 1390 KG / SQ. METERS
COOLANT TEMP. DROP = 22° F
10,000
1,000
100
10
1
0.1
100
1,000
10,000
100,000
HEAT LOAD, KCAL / HOUR

FIGURE 4

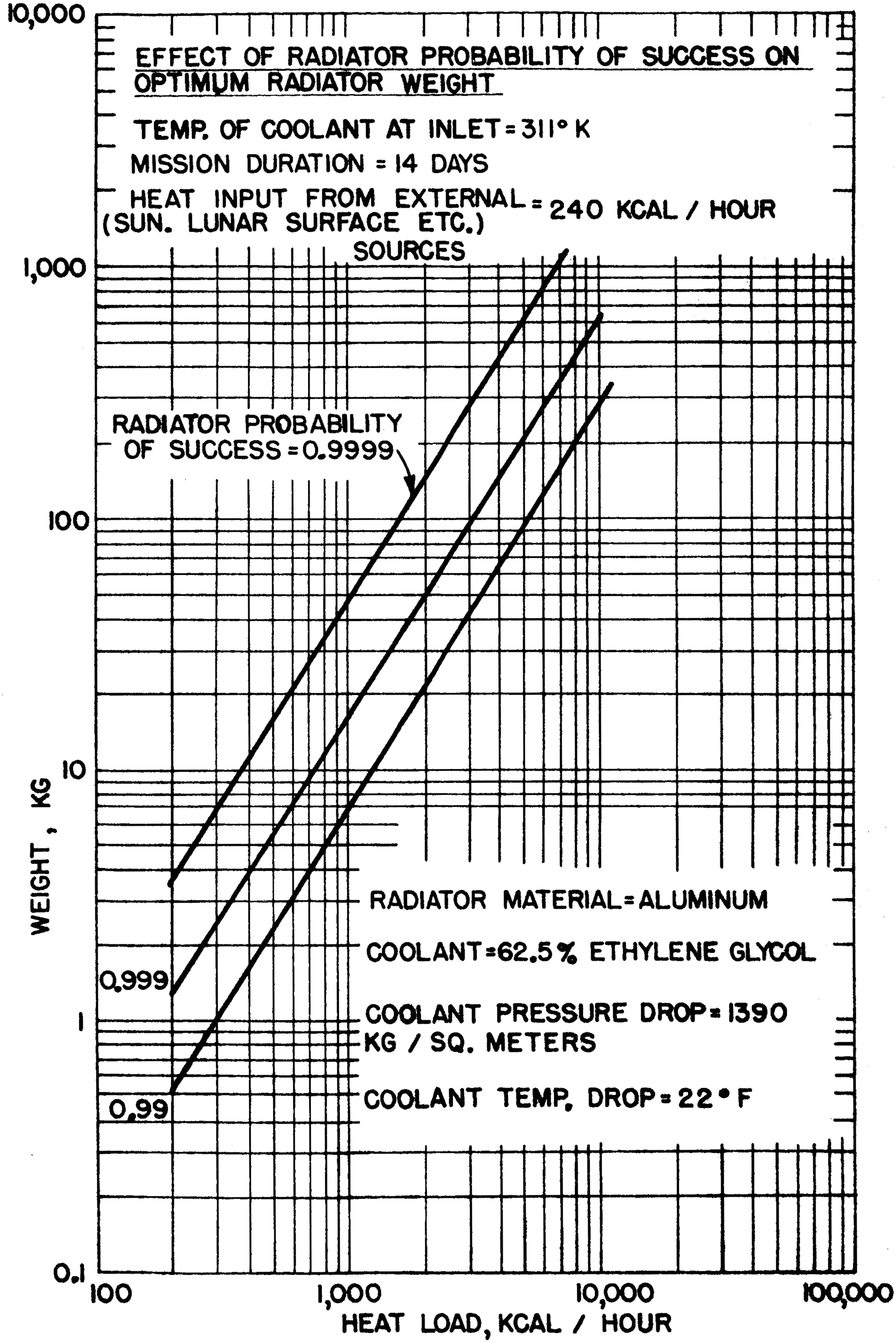
EFFECT OF RADIATOR PROBABILITY OF SUCCESS ON OPTIMUM RADIATOR WEIGHT
TEMP. OF COOLANT AT INLET = 311° K
MISSION DURATION = 14 DAYS
HEAT INPUT FROM EXTERNAL (SUN. LUNAR SURFACE ETC.) SOURCES = 240 KCAL / HOUR
RADIATOR PROBABILITY OF SUCCESS = 0.9999
0.999
0.99
RADIATOR MATERIAL = ALUMINUM
COOLANT = 62.5 % ETHYLENE GLYCOL
COOLANT PRESSURE DROP = 1390 KG / SQ. METERS
COOLANT TEMP. DROP = 22 ° F
WEIGHT, KG
10,000
1,000
100
10
1
0.1
100
1,000
10,000
100,000
HEAT LOAD, KCAL / HOUR

FIGURE 5

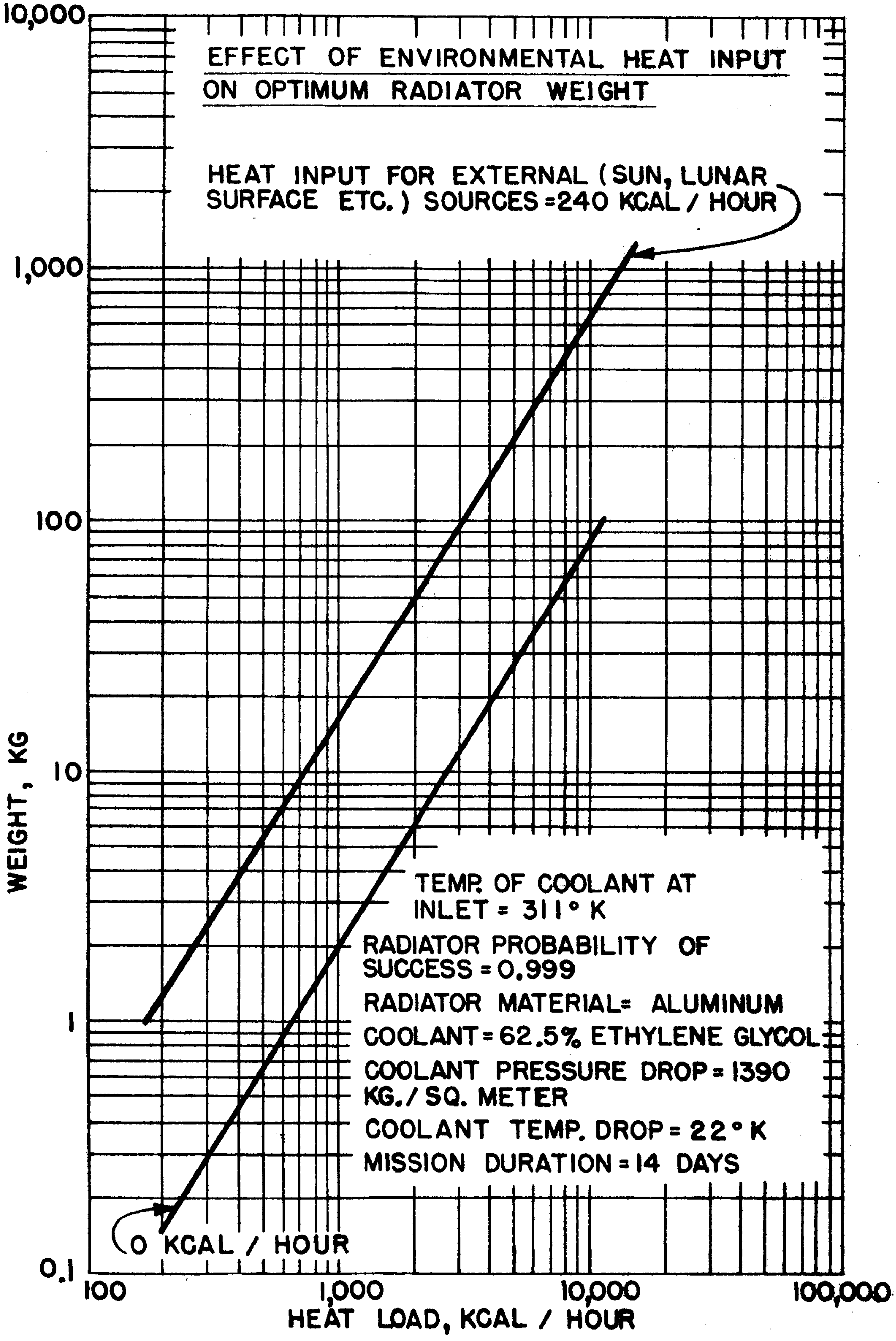
EFFECT OF ENVIRONMENTAL HEAT INPUT ON OPTIMUM RADIATOR WEIGHT
HEAT INPUT FOR EXTERNAL (SUN, LUNAR SURFACE ETC.) SOURCES = 240 KCAL / HOUR
0 KCAL / HOUR
TEMP. OF COOLANT AT INLET = 311° K
RADIATOR PROBABILITY OF SUCCESS = 0.999
RADIATOR MATERIAL = ALUMINUM
COOLANT = 62.5% ETHYLENE GLYCOL
COOLANT PRESSURE DROP = 1390 KG./SQ. METER
COOLANT TEMP. DROP = 22° K
MISSION DURATION = 14 DAYS
WEIGHT, KG
10,000
1,000
100
10
1
0.1
100
1,000
10,000
100,000
HEAT LOAD, KCAL / HOUR

FIGURE 6

EQUILIBRIUM CONCENTRATION FOR A STACK HAVING A LINEAR TEMPERATURE GRADIENT WITH ONE END AT T, THE OTHER AT 90°C NO SINKS OR SOURCES OF WATER

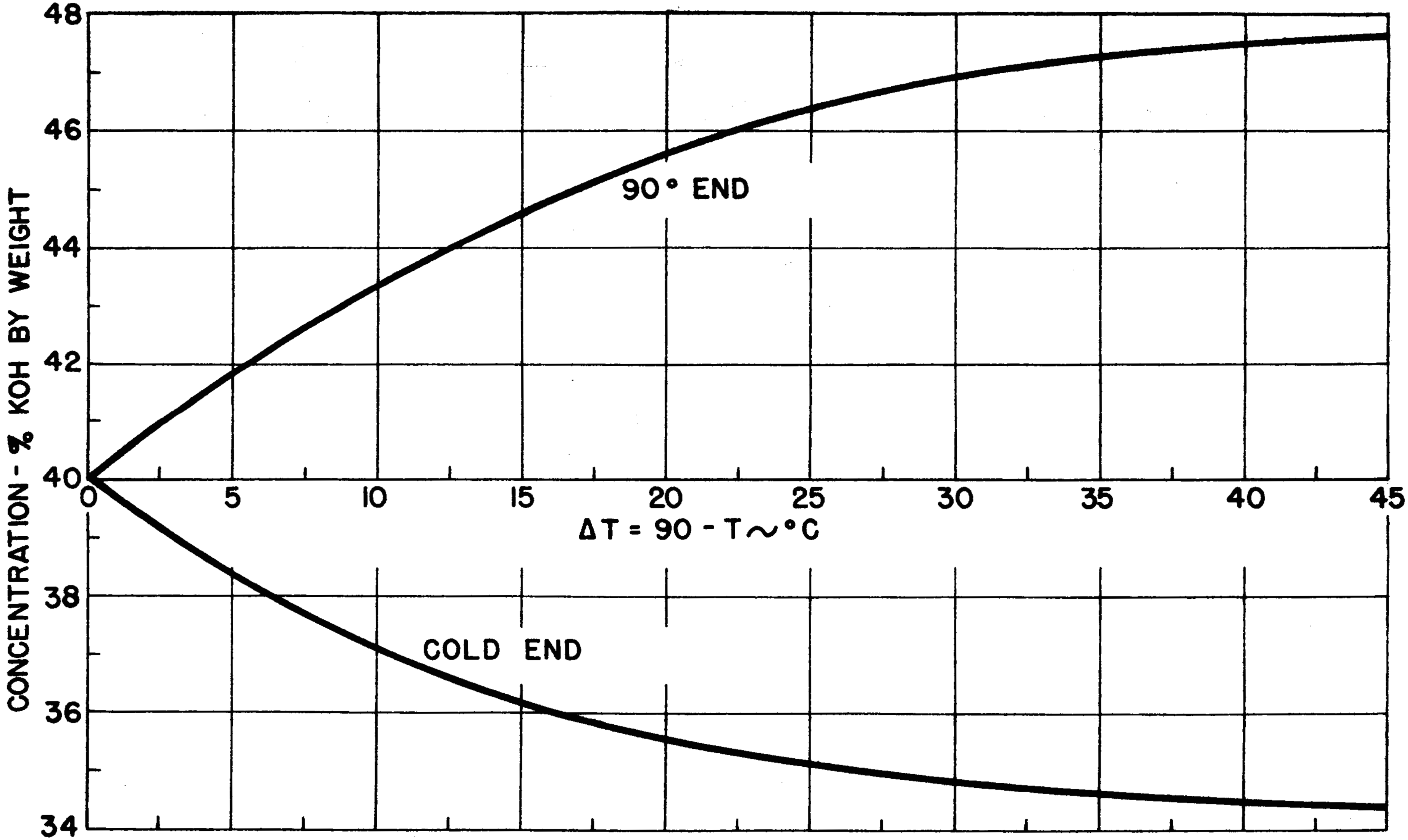

FIGURE 7

RELATIVE VOLUME OF KOH SOLUTION AT ROOM TEMPERATURE - 40% KOH IS BASE

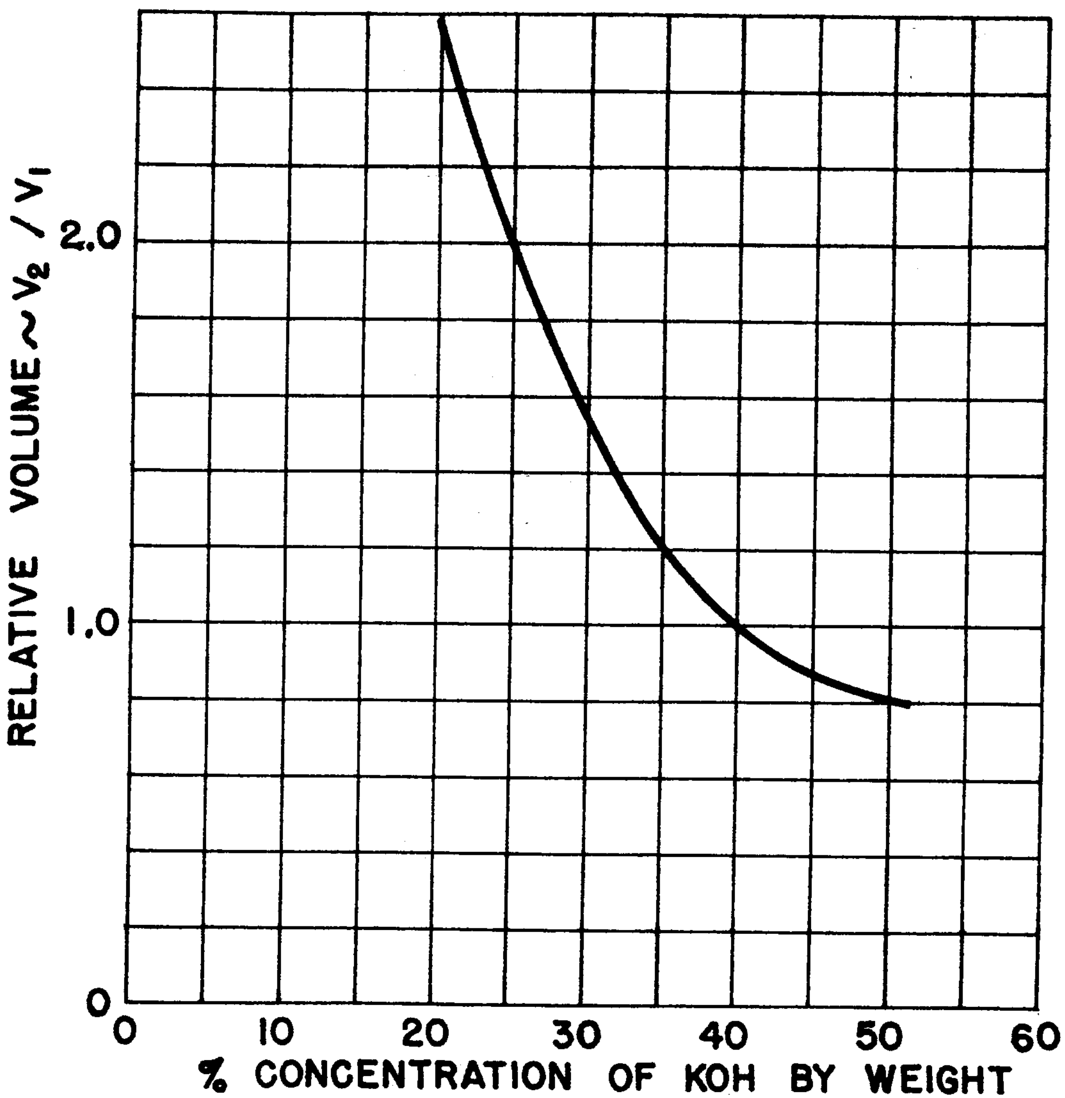

FIGURE 8

EQUILIBRIUM PARTIAL PRESSURE OF WATER VAPOR OVER KOH SOLUTION FOR A SEALED FOR A SEALED SYSTEM HAVING NO SOURCES OR SINKS AND A LINEAR TEMPERATURE GRADIENT $\Delta T = 90 - T$

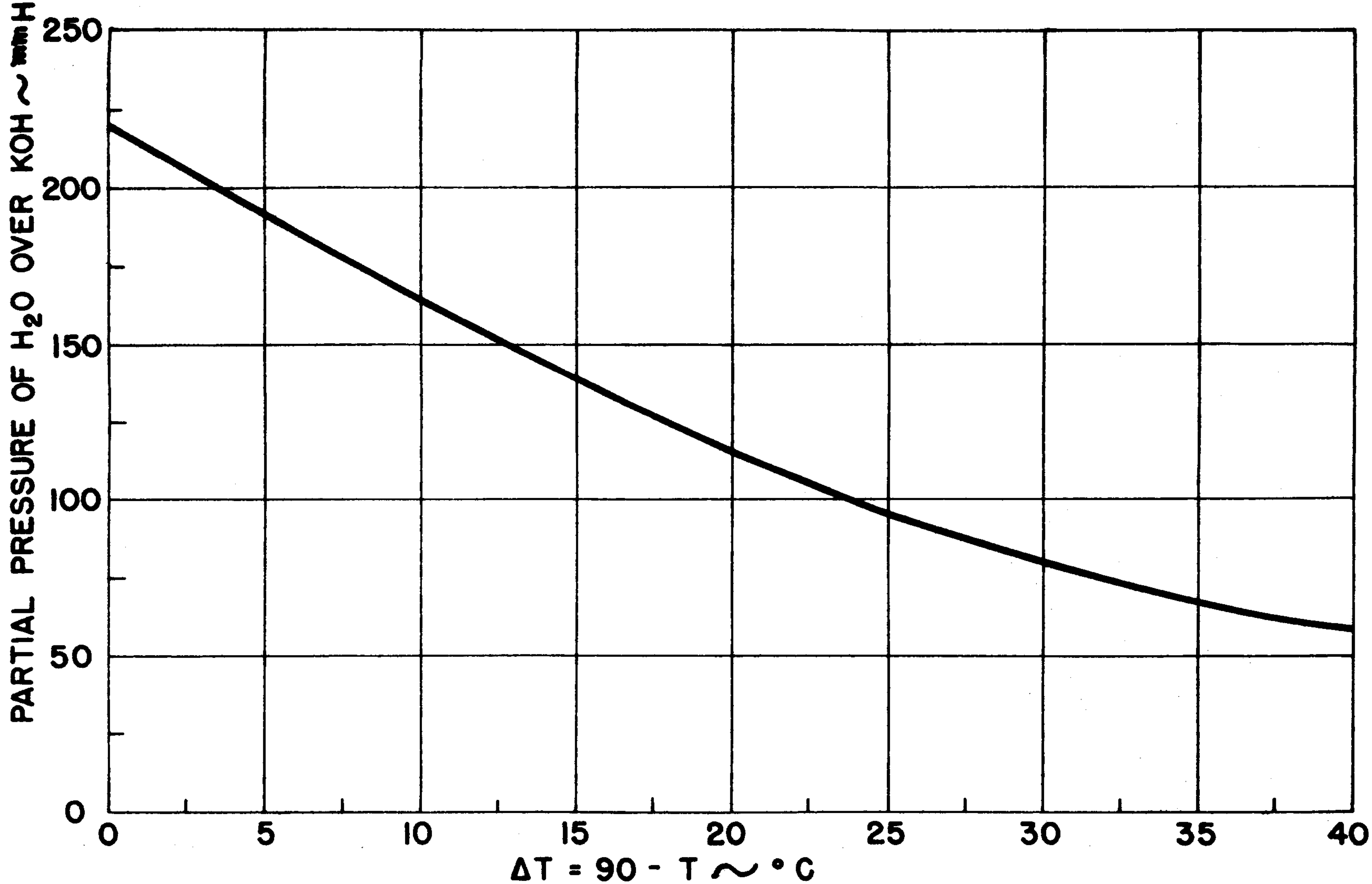

FIGURE 9